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Semi-annual report on activities associated with the MODIS task:

Global Monitoring of Aerosol Properties, Water Vapor, Cloud Structure and Fires

by
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a. Task Objectives (based on the funded proposal)

Introduction

The overall objective of this investigation is to develop algorithms, based on the unique properties of the MODIS sensor, for remote sensing of aerosol and cloud characteristics, and remote sensing of water vapor. The derived aerosol, cloud and water vapor properties will be used to develop aerosol climatology, to perform atmospheric corrections of the MODIS imagery in the solar region, as well as to conduct studies of the environment. These remote sensing products, derived from the MODIS imagery, will contain a unique source of information that will be used to answer basic scientific questions regarding the impact of human activity on the environment:

- What is the contribution of tropical biomass burning on atmospheric concentrations of trace gases and the resulting climate change and changes in atmospheric chemistry.

- What is the effect of particulates formed in the air, from emission of SO_2 in the process of fossil fuel burning, on counteracting the greenhouse effect of the emitted CO_2.

- What is the effect of anthropogenic pollution on natural vegetation and on the quality of life in a densely populated urban environment.

- How do clouds interact with aerosol and water vapor, and what is the impact of this interaction on cloud microphysics, structure and climate.

The team member leads 6 core products and one post launch products, as well as 7 scientific investigations using MODIS data.

Algorithm development

Aerosol: The aerosol optical thickness will be sensed in spectral bands and over surface covers that provide low surface reflectance. This method will be combined with Tanre's contrast method. The spectral dependence of the detected radiances will be used to infer the size distribution of the aerosol and thus the type of aerosol present. Radiances detected over the land will also be used to derive the aerosol single scattering albedo. Algorithms will be developed for routine analysis of global aerosol distribution and characteristics.

Atmospheric corrections: The derived aerosol characteristics, supplemented by aerosol climatology, and information on subpixel clouds and water vapor, will be used to perform atmospheric corrections of the MODIS imagery. Algorithms for routine correction of the satellite imagery will be developed. The application of atmospheric correction to the vegetation index composite will be studied, and an effort will be placed to develop alternative vegetation indexes that are less dependent on atmospheric characteristics.

Water vapor: The newly approved water vapor channels on MODIS in the near IR will be used to derive water vapor from space. The uniqueness of this technique is that it is sensitive to water vapor in the boundary layer. Using upper atmospheric water vapor derived from the IR channels (Menzel's proposal), the boundary layer water vapor can be derived.

Cloud structure: Methods will be implemented to study individual cloud structure and the cloud field structure, using the MODIS 220 m resolution channels. Cloud structure is strongly related to atmospheric dynamics, and thus to the role of clouds in climate. Cloud fractal ratio will be derived and related to other cloud characteristics such as temperature, albedo and microphysics (King's and Menzel's proposals) and the aerosol and water vapor abundance and distribution.

Thermal anomalies: The mid-IR (3.75µm) and the IR (11 µm) channels will be used to determine the presence of thermal anomalies, to count the number of fires, and estimate their sizes (including subpixel size) and temperature. Now that the maximal detectable temperature at the 3.75 µm channel was increased to 700°K, this procedure should be successful.

Scientific investigations

Biomass burning: A global assessment of the contribution of biomass burning to climate change (trace gases and particulates emission) will be based on the detection of fires from MODIS images. The visible and near IR channels will be used to estimate the emission of particulates and trace gases (CO, CH_4, N_2O, etc.) to the atmosphere. Ground and aircraft observations, GOES, HIRIS and MISR imagery will be used to validate and enhance the technique.

Aerosol Effect on clouds and radiation: The methods for remote sensing of aerosol characteristics will be combined with methods for remote sensing of cloud characteristics, in order to determine on a statistical basis the effect of particulate pollution on cloud microphysics and albedo, and its impact on climate.

Aerosol climatology and evolution: MODIS observations of aerosol optical thickness, particles size and single scattering albedo, enhanced by measurements from HIRIS and MISR and combined with intensive measurements from the ground of the spectral optical thickness, the path radiance and the surface irradiance, will be used to generate aerosol climatology and to study sources, transport and sinks of atmospheric aerosol.

Aerosol impact on vegetation, and urban environment: MODIS observations of aerosol transport and deposition, will be used to study the direct effect of aerosol on the natural and anthropogenic environment. It will also be used as a tracer of the presence of other pollutants in the environment and their effect.

Water vapor and the environment: The derived concentration of water vapor will be used to study the interaction of water vapor with vegetation, and the relations between water vapor distribution aerosol and cloud characteristics.

b. Work Accomplished

Most of the work reviewed below was initiated well before the last 6 months (sometimes 4 years ago) but some parts of it were performed in the last 6 months, and it has a direct relevance to the MODIS investigation.

New approach for aerosol remote sensing over land

One of the methods for remote sensing of aerosol loading is based on remote sensing of aerosol over dark terrain. If the terrain is well characterized, (e.g. dense forest) its reflection in the red and blue channels can be assumed a priori and used to derive the aerosol optical thickness from the measured radiance in these two bands, and some information on the aerosol size distribution. In the past the Vegetation index was used to identify dark vegetated pixels for this purpose. But the vegetation index itself is sensitive to the presence of aerosol and therefore cannot be used efficiently when the concentration of aerosol particles varies spatially. A study is being conducted to try and identify the proper pixels by using a mid IR channel. It was found that the surface reflectance in the 3.75 μm channel is highly correlated with the surface reflectance in the 0.65 or 0.47 μm channels, over regions that include vegetation. The reason is that vegetation darkens the visible channel by the chlorophyll absorption. Liquid water is associated with the presence of live vegetation and therefore with the presence of chlorophyll. Wet soils are darker in the visible part of the spectrum due to light trapping mechanism, and they are also darker in the mid-IR due to liquid water absorption. In the study the AVHRR images are being used. It is possible that the 2.2 μm channel on MODIS can be also very useful for this purpose.

Atmospherically resistant vegetation index - ARVI for EOS-MODIS

A paper was published by Kaufman and Tanre (1992) on the development of an atmospherically resistant vegetation index, ARVI, to be used for remote sensing of vegetation from the MODIS sensor. The index takes advantage of the presence of the blue channel (0.47±0.01 μm) in addition to the red (0.66±0.025 μm) and the near IR (0.865±0.02 μm) channels that compose the present normalized difference vegetation index - NDVI. The resistance of the ARVI to atmospheric effects (in comparison to the NDVI) is based on two principles:

- The reflectance of surface covers is similar in the red and the blue channels
- The atmospheric effect in the blue channel is about twice that in the red channel.

As a result the following function:

$$L_{rb}=2L_r-L_b$$

(where L_r is the reflectance in the red channel and L_b is the reflectance in the blue channel), is sensitive to the surface properties in a similar way to the sensitivity of the red radiance, but its sensitivity to the atmosphere is canceled in the process of subtraction. As a consequence L_{rb} is used instead of L_r in the computation of the vegetation index.

Simulations using radiative transfer computations on arithmetic and natural surface spectra, for various atmospheric conditions, show that ARVI has a similar dynamic range to the NDVI. Due to the excellent atmospheric resistance of the ARVI, it is possible that remote sensing from MODIS of the vegetation index over most land surfaces will include molecular and ozone correction with no further need for aerosol correction, except for dust conditions, like in the Sahel.

Acquirement of air/ground truth data

There is an urgent need for data set that relate the surface and atmospheric properties to the radiance field that can be detected by the MODIS system. Since only partial data sets are available in the literature, we are engaged in collection of such data sets.

A field experiment was conducted in desert transition area in Israel, in collaboration with the Israeli Desert Institute. The purpose of the experiment is to collect measurements of the angular reflection of surface features in this terrain in the visible (including the blue) and near-IR bands, simultaneously with atmospheric aerosol measurements. The experiment utilizes a new/old technique of quantitative photography. The measurements will be used to test new concepts of remote sensing of aerosol, atmospherically resistant vegetation indexes and atmospheric correction techniques. Yoram Kaufman, Brent Holben, Lorraine Remer and William Lazenby (Wallops) participated in the experiment. A similar, smaller experiment was conducted last summer around NASA/Wallops. The data are being analyzed and a paper is being written. Although quantitative photography suffers from nonlinear calibration, and sensitivity to development conditions, it is shown that careful photography using separate cameras for each spectral band, and development of the film with calibration stripes in a well controlled environment result in an accurate radiometry. Photographic film offers best possible spatial resolution, and can store large quantities of data. The systems of cameras is portable and easily adjustable to different aircraft systems.

Aerosol climatology

A paper was accepted for publication in JGR: "Measurements of the Aerosol Optical Thickness and Atmospheric Path Radiance - implication to aerosol remote sensing and atmospheric corrections". The paper offers and analysis of aerosol climatology that is not based on the conventional assumptions of aerosol homogeneity and sphericity.

Spaceborne remote sensing of aerosol particles, evaluation of the climatic effects of aerosol and atmospheric corrections of spaceborne imagery of the earth's surface, are based on an assumed relationship between the spectral aerosol optical thickness and the spectral path radiance. Path radiance is the radiance detected by a spaceborne sensor above a nonreflective surface, and is the result of backscattering by particles and molecules in the atmosphere. In specific measurement conditions the path radiance can be measured also from the ground. Simultaneous measurements of the path radiance and the optical thickness from the ground are reported in this paper at over 30 locations spread all over the world. The measurements cover different aerosol types and climatic conditions. All the measurements are performed with a single 8 channel portable sunphotometer/ radiometer in the 0.44-1.03 µm range. The observations are taken for constant solar and view directions, resulting in a constant scattering angle of 120°, which resembles space observations.

One set of measurements is used to develop empirical relations among the aerosol spectral optical thickness and the scattered spectral path radiance. A second, independent set is used to test these relations. It is shown that simple measurements performed from the ground, can yield empirical relations that can replace some of the common, but not validated assumptions about the particle homogeneity, sphericity, composition and size distribution, used in remote sensing models and in estimates of the radiative effects of aerosol. Results are summarized in Table 1 below and used to test concepts of atmospheric corrections.

After completion of this project the radiation measurements were expanded to include the whole plane in the sky that includes the sun. The data from US, Europe and Israel are being analyzed.

Table 1: *Summary of the accuracy of derivation of optical thickness, τ, and path radiance, L_{pd} one from another using empirical relations derived from measurements from the first data set and tested against a second data set.*

Derivation of	from	error predicted from first data set	error derived based second data set
τ_{872}	τ_{613}	$\Delta\tau = \pm 0.03$	$\Delta\tau = \pm 0.029$
τ_{441}	τ_{613}	$\Delta\tau = \pm 0.03$	$\Delta\tau = \pm 0.034$
$L_{pd}(0.872\mu m)$	$L_{pd}(0.522\mu m)$	$\pi\Delta L_{pd}/F_o = \pm 0.002$	$\pi\Delta L_{pd}/F_o = \pm 0.002$
$L_{pd}(0.613\ \mu m)$	$\tau(0.613\ \mu m)$	$\pi\Delta L_{pd}/F_o = \pm 0.008$	$\pi\Delta L_{pd}/F_o = \pm 0.007$
$\tau(0.613\ \mu m)$	$L_{pd}(0.613\ \mu m)$	$\Delta\tau = \pm 0.06$	$\Delta\tau = \pm 0.059$
$\tau(0.872\ \mu m)$	$L_{pd}(0.872\ \mu m)$	$\Delta\tau = \pm 0.04$	$\Delta\tau = \pm 0.028$
α_τ	α_L	$\Delta\alpha_\tau=\pm 0.5.$	$\Delta\alpha = \pm 0.3$

τ is the aerosol optical thickness in the specified wavelength
L_{pd} is the path radiance measured from the ground (and representative of the phase function as measured from space).
α_τ and α_L are the spectral dependencies of the optical thickness and the path radiance respectively.

Effect of Amazon smoke on cloud microphysics and albedo - analysis from satellite imagery

A paper on this subject was accepted for publication in J. Appl. Meteor., special issue for the memory of P. Squires. The paper studies the aerosol-cloud interaction and shows that it can be retrieved from satellite observations for cumulus and stratocumulus clouds.

NOAA-AVHRR images taken over the Brazilian Amazon basin during the biomass burning season of 1987 are used to study the effect of smoke aerosol particles on the properties of low cumulus and stratocumulus clouds. The reflectance at a wavelength of 0.64 µm and the drop size, derived from the cloud reflectance at 3.75 µm, are studied for tens of thousands of clouds. The opacity of the smoke layer adjacent to each cloud is also monitored simultaneously. Though from satellite data it is impossible to derive all the parameters that influence cloud properties and smoke cloud interaction (e.g. detailed aerosol particles size distribution and chemistry, liquid water content etc.); satellite data can be used to generate large scale statistics of the properties of clouds and surrounding aerosol (e.g. smoke optical thickness, cloud drop size and cloud reflection of solar radiation) from which the interaction of aerosol with clouds can be surmised. In order to minimize the effect of variations in the precipitable water vapor and in other smoke and cloud properties, biomass burning in the tropics is chosen as the study topic, and the results are averaged for numerous clouds with the same ambient smoke optical thickness.

It is shown in this study that the presence of dense smoke (an increase in the optical thickness from 0.1 to 2.0) can reduce the remotely sensed drop size of continental cloud drops from 15 µm to 9 µm. Due to both the high initial reflectance of clouds in the visible part of the spectrum and the presence of graphitic carbon, the average cloud reflectance at 0.64 µm is reduced from 0.71 to 0.68 for an increase in smoke optical thickness from 0.1 to 2.0. The measurements are compared to results from other years, and it is found that, as predicted, high concentration of aerosol particles causes a decrease in the cloud drop size, and that smoke darkens the bright Amazonian clouds. Comparison with theoretical computations based on Twomey's (1977) model show that using the measured reduction in the cloud drop size due to the presence of smoke it is possible to explain the reduction in the cloud reflectance at 0.64 µm for smoke imagery index of -0.02 to -0.03.

Smoke particles are hygroscopic and have a similar size distribution to maritime and anthropogenic sulfuric aerosol particles. Therefore these results may also be representative of the interaction of sulfuric particles with clouds.

c. Anticipated future action

- Analysis of the data collected in Israel and generation of a simulation data sets that includes surface reflectance properties in the blue, red and near-IR channels.
- Analysis of AVIRIS and TM data for the same purpose as well as for analysis of remote sensing of water vapor in the near-IR and the correlation between the visible and mid-IR channels.
- Analysis of MAS data over the land areas of interest to this project.
- Preparation for field experiment in Brazil.
- Visit the Joint Research Center in Ispra, Italy (July) to coordinate activities for measurements of aerosol climatology and simultaneous TM imagery.
- Acquire automatic instruments to measure aerosol properties and their interaction with radiation, to be deployed in several sites and generate global data sets.
- Continues simulations and verifications against aircraft measurements of ARVI.
- Analysis of 3 years of aerosol and radiation data taken in the US Europe and Israel.

d. Problems/ Corrective actions

There is a need for data sets that relate the earths surface properties across the MODIS bands. E.g. measurements of reflection in the visible and mid IR simultaneously with measurements in the mid IR. There is hope that in the near future the MODIS simulator will provide some of these data.

e. Publications (Papers that appeared or were accepted during the last 6 months)

MODIS initiated

Kaufman, Y. J. and B.C. Gao, 1992: 'Remote sensing of water vapor in the near IR from EOS/MODIS', IGARS, May 1990, *IEEE Geosc. and Rem. Sens.* in press

Kaufman, Y. J. and D., Tanré, 1992: Atmospheric Resistant Vegetation Index, *IEEE J. Geosc. Rem. Sens.,*, 30, 261-270.

Kaufman, Y. J., 1992: 'Measurements of the aerosol optical thickness and the path radiance - implications on aerosol remote sensing and atmospheric corrections', JGR-Atmospheres, in press.

King, M.D. Y.J. Kaufman, P. Menzel and D. Tanre, 1992: 'Determination of cloud, aerosol and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS), *IEEE J. Geosc. and Rem. Sens.* 30, 2-27.

Other related papers

Andreae, M.O., A. Chapius, B. Cros, J. Fontan, G. Helas, C. Justice, Y.J. Kaufman, A. Minga, D. Nganga, 1992: 'Ozone and Aitken Nuclei over Equatorial Africa: Airborne observations during DECAFE 88', *J. Geoph. Res.* in press

Fraser, R.S., R.A. Ferrare, Y.J. Kaufman and S. Mattoo, 1992: 'Algorithm for atmospheric corrections of aircraft and satellite imagery', *Int. J. Rem Sens.* 13, 541-557.

Holben, B.N., E. Vermont Y.J. Kaufman, D. Tanré and J. Kalb, 1992: 'Atmospheric correction methods for the AVHRR', *IEEE J. Geosc. and Rem. Sens.* , 30, 212-222.

Kaufman, Y. J. and Nakajima, T., 1992: ‘Effect of Amazon smoke on cloud microphysics and albedo’, accepted to *J. Appl. Meteor, Squires special issue*.

Kaufman, Y. J., A. Setzer, D. Ward, D. Tanre, B.N. Holben, P. Menzel, M.C. Pereira and R. Rasmussen, 1992: Biomass Burning Airborne and Spaceborne Experiment in the Amazonas (BASE-A), *J. Geoph. Res,* in press.

Tanré, D., B.N. Holben and Y.J. Kaufman, 1992, Atmospheric correction algorithm for NOAA-AVHRR products, theory and application, *IEEE J. Geosc. Rem. Sens.*, 30, 231-248.

Ward, D.E., R. Susott, J. Kauffman, R. Babbitt, B. N. Holben, Y.J. Kaufman, A. Setzer, R. Rasmussen, D. Cumming and B. Dias, 1992: Emissions and burning characteristics of biomass fires for cerrado and tropical forest regions of Brazil - BASE-B experiment’, submitted to J. Geophys. Res.